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Guidelines for the Use of Unmanned Aerial Systems in Flood Emergency Response

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Abstract: There is increasing interest in using Unmanned Aircraft Systems (UAS) in flood risk management activities including in response to flood events. However, there is little evidence that they are used in a structured and strategic manner to best effect. An effective response to flooding is essential if lives are to be saved and suffering alleviated. This study evaluates how UAS can be used in the preparation for and response to flood emergencies and develops guidelines for their deployment before, during and after a flood event. A comprehensive literature review and interviews, with people with practical experience of flood risk management, compared the current organizational and operational structures for flood emergency response in both England and India, and developed a deployment analysis matrix of existing UAS applications. An online survey was carried out in England to assess how the technology could be further developed to meet flood emergency response needs. The deployment analysis matrix has the potential to be translated into an Indian context and other countries. Those organizations responsible for overseeing flood risk management activities including the response to flooding events will have to keep abreast of the rapid technological advances in UAS if they are to be used to best effect.

Keywords: drone applications; deployment time; monitoring; flood modelling; evacuation; rescue; resilience

1. Introduction

In recent decades, significant flood events have affected many countries around the world including those caused by Hurricane Katrina (Florida and Louisiana, August 2005), Hurricane Leslie (France, October 2018) and the 2018 monsoon season in India (Kerala, August 2018). The impacts of these flood events on people and communities are wide and varied and can be catastrophic. The Katrina floods resulted in over 1100 deaths in Louisiana [1], with estimated economic losses of $149 billion [2]; the 2018 floods in France resulted in 14 deaths and over $500 million of damage [3]; whilst the 2018 Kerala in India floods resulted in more than 400 deaths, displaced 1.8 million people and caused an estimated $3 billion worth of damage [4]. The last major flood event in England took place in winter 2015/2016, with December 2015 being the wettest month ever recorded in England. A total of 17,000 properties across the north of England were affected with named storms Desmond, Eva and Frank. The total economic damages were estimated to be £1.6 billion [5].

Effective and efficient flood emergency response has a key role in reducing the adverse impacts of flooding. Coordinating the response—including warning and informing prior to and during events, evacuation prior to the flooding, the rescue of people and the organization of volunteers [6]—has been a priority for governments in recent decades. Although there are clearly lessons to be learned from experiences in other countries, often the detailed arrangements need to be context specific.

In England, revised flood emergency operational arrangements were put in place building on the experience to date. These are outlined in the National Flood Emergency Framework [7]. The primary aims of the emergency response include the protection of human life, the alleviation of suffering and the restoration of disrupted services (e.g., water, electricity, transport). Within this framework and based on documented command and control protocols, decisions are taken at the lowest appropriate level with coordination at the highest necessary level.

In India, the Central Government has established the National Disaster Management Division within the Ministry of Home Affairs. This Division has introduced various initiatives and set up several organizations to deal with disasters, including floods. In 2016, a National Disaster Management Plan was published to provide the overall direction and national goals. Under the plan, the various ministries and departments at state and district levels have to develop their own specific management and response plans, and related operating procedures [8].

Various emergency response activities rely on the information provided by monitoring, models and multiple data sources. For example, in India hydrological and flood models are used by the Central Water Commission for modelling and forecasting purposes [8] to provide water level and river flow information to the authorities [9] with an online dissemination portal [10]. In England, there has been a continuing interest in developing flood models for fluvial, pluvial and sea flooding [11], with different data needs and outcomes [11,12], to help reduce the impacts on people, property and critical infrastructure [13]. From the response side, emergency responders request and collate a varied range of information, from aerial imagery to individual eyewitness reports, to support decision-making. Different information is required pre-, during- and post-events. For instance, during a flood event real-time or near real-time local information on how many people, buildings, and other infrastructure are at risk is required [14]; post-event aerial imagery can provide vital and detailed information about the extent of flooding and damage to properties [15].

In recent years, emergency responders have used Unmanned Aircraft Systems (UAS) to acquire core information pre-, during- and post-events [16–18]. UAS are small and light (less than 20 kg) remotely piloted aircraft generally equipped with a range of sensors for the collection of information. There are two main types of UAS platforms: fixed wing and vertical take-off and landing (VTOL). The former relies on wings that generate lift to fly, whereas VTLO rely on rotors. UAS can be equipped with different sensors [19] from cameras to warning systems. RGB cameras are able to provide high resolution imagery of up to 2 cm. Emergency responders in various countries have identified the added benefits of UAS in humanitarian responses in terms of the rapid assessment of damage, such as collapsed buildings or blocked roads and search and rescue operations [20,21]. In England for example, during winter 2015/2016, UAS were used by the Environment Agency (EA) to assess smaller scale flooding incidents in high detail; in particular, UAS were used to provide an up close and detailed live stream of an inaccessible river breach. This enabled an effective and efficient assessment of the area [22]. However, the rapid uptake and continuous development of the technology have resulted in the ad-hoc and opportunistic use of UAS over a strategic appraisal of how best to use them and for what purpose pre-, during- and post-events. Various types of UAS missions have been identified as being used in flood emergency responses (including strategic situation awareness, inspections, ground search, water search, debris/flood/damage estimation and tactical situation awareness) with an indication of the data products (e.g., images, videos, and orthomosaics) generated in the flights [18]). However, there is not yet a purpose-driven approach defining which UAS products would be of benefit at each stage of the preparation for and response to a flood event. The need of such logic-based decision support approach has been identified by multiple research and governmental organizations within the context of catastrophe response in India and England through two knowledge exchange workshops organized in Delhi (30 September 2018) and Bangalore (18 September 2019) within the engagement activities organized by the EPSRC research project 'Emergency flood planning and management using unmanned aerial systems' (www.efloodplan.net). To the authors' knowledge, a purpose-driven approach detailing how and when UAS with specific embedded sensors should be used to collect data to assist in flood event responses is not yet documented. It is envisaged that such an approach will be context-specific and influenced by the nature of the flood events that occur within a particular area, region or country, the data available from other sources, as well as the airspace regulatory framework for UAS use.

Based on these premises, the aim of this study is to develop purpose led guidelines for the efficient and effective deployment of UAS for flood risk management activities including emergency response pre-, during- and post-event phases. We demonstrate how a deployment analysis matrix can be designed and used to assist flood emergency response requirements in the context of catchment response and the nature of flood events for England and explore its potential to be translated into an Indian context. This will be achieved through the following four overarching objectives: (1) to map out the current role of existing organizations involved in emergency response in England and India; (2) to identify existing UAS applications within the components of a flood risk management system; (3) to determine context-specific requirements for UAS products to assist in flood risk management activities; and, (4) to develop an adaptive and transferable matrix analysis framework that can then be used as the basis for guidelines for the effective deployment of UAS for flood risk management activities leading to more resilient urban environments and including emergency response before, during and after a flood event.

2. Materials and Methods

2.1. Flood Emergency Response in England and India and the Potential Use of UAS

The institutional arrangements for flood emergency response and the current and potential applications of UAS technology were determined through a literature review and face-to-face interviews with key personnel with detailed understanding of the flood response arrangements in England and in India. England and India were selected for this study based on recent flood events occurring in these areas (Cockermouth, England, 2015 and Kerala, India, 2018). A total of 14 interviews were held in India (7) and England (7), including participants with experience in flood emergency response from the national and regional authorities, private sector and Non-governmental organizations (NGOs). A semi-structured questionnaire based on a set of twenty open questions was used (Supplementary Materials). This format enabled the interviews to be focused on the research objectives, but with the flexibility to evaluate responses and explore issues that emerged during interviews. The raw data products (i.e., those are provided without extra processing or internet connection) and derived products (i.e., produced by post-processing of the raw data products) produced by UAS applications, as well as the key factors affecting UAS deployment and flight plan configuration were also identified in the literature review. Additional information on the main applications and potential use of UAS was also obtained from a knowledge exchange workshop organized in India within the engagement process of the EPSRC research project "Emergency flood planning and management using unmanned aerial systems" (Delhi, 30 May 2018). The UAS applications were grouped into a set of five flood management components, which included flood warning, flood monitoring and flood risk assessment, evacuation route identification, damage assessment and rescue.

2.2. Development of an UAS Deployment Analysis Matrix

This study uses a 3 × 3 matrix to identify potential uses of UAS in flood risk management activities and as the basis of guidelines on the deployment of UAS for flood risk management activities. A number of factors were considered for the x and y axes of the matrix when considering UAS deployment and flight plan configurations. The three main factors identified were related to catchment size, flood source type, and phase of a flood event (Table 1). Catchment size influences the amount of data gathered [23] and the type of UAS that is required to provide the spatial coverage [24].

Catchment flood response was chosen as one of the key factors because this gives an indication of the time available to deploy an UAS and the use of particular applications and technologies in a given situation. The catchment flood response was determined based on the time between the start of a rainfall event and the potential for the flooding of properties. Based on climatic and catchment conditions in England, the flood response was considered to be 'slow' when flooding occurs more than 8 h after the rain event, 'medium' when flooding occurs between 3 and 8 h and 'fast' when the onset of flooding takes place in less than 3 h [25,26]. We also considered in the deployment analysis matrix the phase in which UAS will be deployed in the overall approach to flood risk management activities [27]: 'pre-event', 'during-event' and 'post-event' (Figure 1). Pre-event refers to activities such as flood modelling activities, the construction of flood risk reduction assets and the planning that will be needed to respond effectively to a defined flood magnitude (i.e., based on a return period). During-event starts as soon as the first flood warning is issued, whilst post-event refers to the recovery and clean-up phase when the water has receded and for example is no longer within people's houses or blocking transport routes.

Table 1. Key factors identified as relevant for the development of the Unmanned Aircraft Systems (UAS) deployment analysis matrix.

Factor		Description
Catchment	Catchment size	Size of the catchment where the event has taken place [23,24]
	Catchment flood response	Catchment response to flooding after the rain event occurs [28,29]
Flood	Flood source type	Source of flooding classified as groundwater, pluvial and fluvial [30]
	Flood extent	The spatial coverage of the flood event and the associated emergency response coverage (e.g., single scene, regional coverage and national coverage) [31]
Response	Emergency response phases	Pre-event, during-event and post-event [27,32]

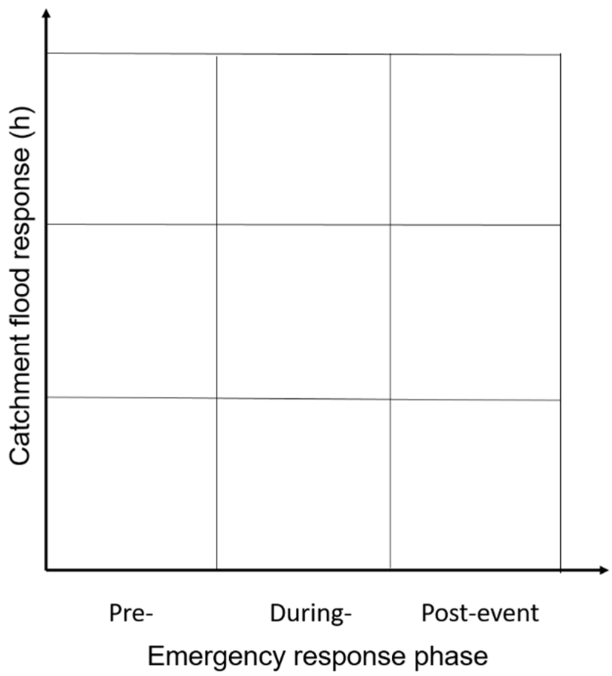

Figure 1. Format of the UAS deployment analysis matrix.

Each of the nine cells within the matrix were populated with the UAS applications identified from the literature review and via a second set of ten one-to-one interviews in England. The interviews targeted specialists in the use of UAS for monitoring, surveying and incident response within the EA, Cranfield University, University of Exeter and an independent expert in flood risk management who had extensive experience of emergency responses at a senior level. During each interview, responders were presented with a set of cards defining the UAS applications, the processing time required to obtain the UAS products and the accuracy or resolution of such products. Processing time, accuracy and resolution were defined based on values reported in the literature. Responders were able to allocate the UAS applications with a given processing time and accuracy within the context of a recent flood event in which they were involved. The data gathered in the matrix was analyzed to identify the consistency between participants in allocating an application to a particular matrix cell. Consistency between participants was assessed through direct comparison of the number of responses per application and cell.

A workshop organized in India (Bangalore, 18 September 2019) helped provide insights about the transferability of the designed deployment analysis to an Indian context. Discussions with experts on flood risk management activities including emergency response in India were held to determine the potential transferability of the matrix to other countries.

2.3. Technological Needs for the Use of UAS in Flood Emergency Response

To assess how the technology should be further developed to meet flood emergency response needs, an extended online survey was also carried out (See Supplementary Materials for details of the survey). The UAS applications—flood extent, flood depth and flow velocity—were selected as they are considered to be key for making decisions during a flood event [33,34]. For the three UAS applications, participants were asked about the current and desired time to process these specific geomatics products and the associated accuracy requirements. Accuracy refers to the expected error range in flood extent (m), flood depth (cm) and flow velocity (m s^{-1}) in the generated geomatics product. The survey was built in Qualtrics software and distributed to relevant experts and at two flood risk management related events: Oasis Conference (London, 18 June 2019) and Flood and Coast (Telford, UK, 20 June 2019). A total of 25 participants completed the survey. Data collected were compared using descriptive statistics to assess the current and desired accuracies and time to process each application. The information gathered enabled an assessment to be made as to whether there are any knowledge and technology gaps that need to be addressed to achieve a desired time and accuracy for a given application.

3. Results

3.1. Organizations Involved in Flood Emergency Response: England and India

Results from the literature review and one-to-one interviews highlighted that in England there are over 17 organizations involved in flood emergency response. This is similar to the number in India, where 16 key organizations were identified (see Supplementary Materials).

In England, the response to localized flooding is led by the local emergency responders without any significant involvement from central government [35]. For some flood events, local responders are supported by central government via Department for Environment, Food and Rural Affairs (Defra) as the designated Lead Government Department for responding to floods. Defra normally co-ordinates the cross-government response to lower level national flooding events (level 1) and manage it within the department. As the extent and impact of the flooding increases, it is likely that there will be increasing involvement by others in central government with the activation of the Cabinet Office Briefing Room (COBR), which brings together ministers, seniors government officials, representatives from national response agencies and organizations impacted by the flood event. Level 2 events (serious impact) are still coordinated by Defra but through COBR. More serious events (level 3—catastrophic) are fully escalated to central co-ordination by the Civil Contingencies Secretariat within COBR [7] (Figure 2). The Army and other military forces may be requested to help in a flood response [36].

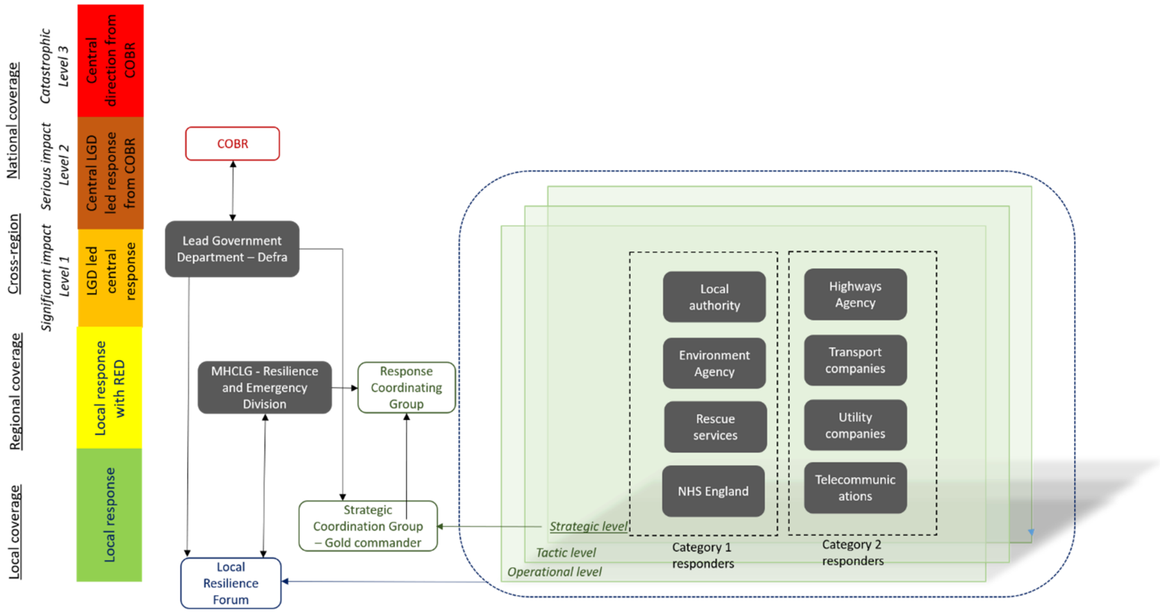

Figure 2. Schematic diagram of flood emergency response in England showing the main agencies and groups involved, the levels of emergency responses at the local level (operational, tactical, strategic), the categories of responding organizations (Category 1 and Category 2) and the likely government arrangements (from local response to central direction from COBR) which depends upon flood extent (local, regional, cross-region and national). Category 1 comprises the organizations that are at the core of the response to most emergencies, whereas Category 2 responders are co-operating bodies involved in incidents that affect their sector. The color schemes in the government arrangements reflect the increasing levels of emergency response (from green to red). COBR: Cabinet Office Briefing Rooms, Defra: Department for Environment, Food and Rural Affairs, MHCLG: Ministry of Housing, Communities and Local Government, RED: Resilience and Emergency Division, and LGD: Lead Government Department.

At present, there are a number of organizations that may use UAS during a flood event. These include the EA, the Fire and Rescue Service, the Police and insurance companies as well as private individuals. As an example, in England, the local or national incident responders may request the deployment of UAS to the specialist Geomatics Team of the EA to provide information related to flood damage and impacts [37]. The Geomatics Team will evaluate if UAS are the most appropriate means of obtaining the information. One of the interviewees informed us that arrangements are in place that allow the EA's Geomatics Team to deploy UAS in any part of England within six hours. The UAS images can be sent via a live feed to an EA incident room. The decision as to who will fly UAS in a particular situation is agreed locally event by event. To date, there is not an established approach to decide which organization will fly UAS for what purpose during and after an event. This can result in a duplication of effort or in important information not being gathered during a particular event.

India also has a tiered approach to flood emergency response (Figure 3). The national government develops policies and provides advice and assistance when there are major events, whilst the States are the responsible for carrying out risk assessments and planning and implementing mitigation measures [8]. At the district level, flood events are categorized into three levels of impact [38]: Level 1—there are sufficient resources and capacity to respond at the district level; Level 2—the impact is beyond existing capacities and support from State agencies is needed; and Level 3—the impact is beyond the existing capacities of district and state resources and support from national agencies is needed (Figure 3). If an emergency escalates beyond their capabilities, the local administration must seek assistance from the district administration or the State Government. If the State Government considers it necessary, it can seek central assistance [8]. The Ministry of Water Resources (river flooding) and Ministry of Urban Development (pluvial flooding) function under the overall guidance of the Ministry of Home Affairs [8,39] when responding to flood events.

In India the police, navy and army have permission to fly UAS for security and rescue reason. However, as in England, there is not an established system to deploy UAS in flood emergency response activities. For example, in the 2013 Uttarakhand floods, the National Disaster Response Force (NDRF) deployed UAS with technical support from research institutions [40,41]. The Indian security forces and the Indo-Tibetan Border Police also deployed UAS to assist in the relief efforts of the National Disaster Response Force by helping find survivors in remote locations [42] and in areas cut off by landslides [43]. During the interviews performed in Delhi, Indian participants highlighted the opportunities to use UAS at the district level by the District Collector, who is responsible for district-level responses to a flooding event.

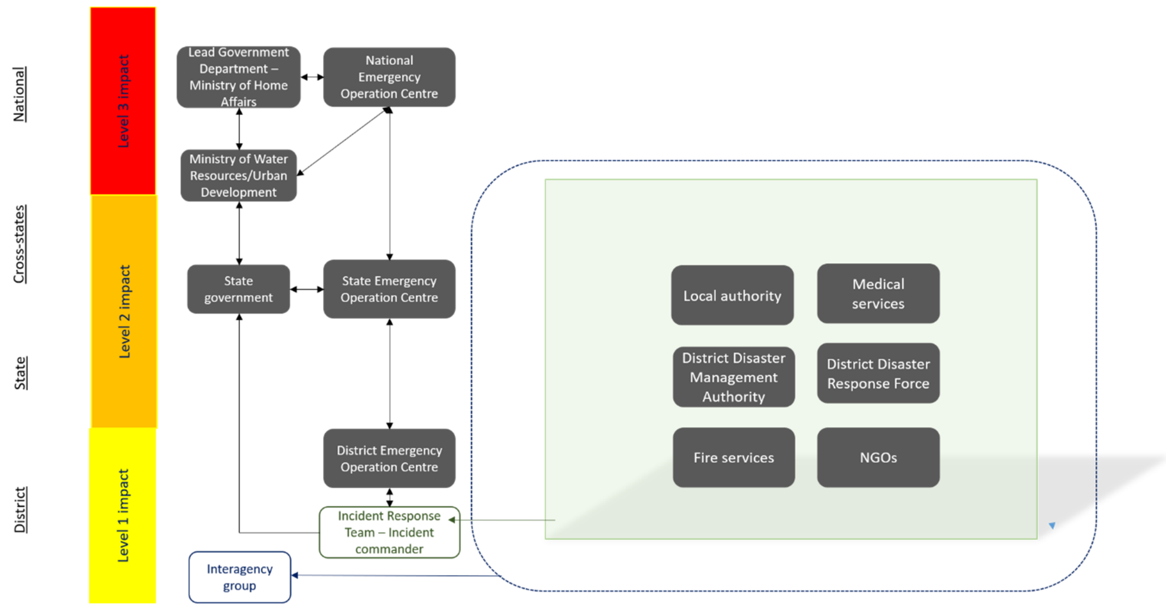

Figure 3. Schematic diagram of flood emergency response in India showing the main agencies and groups involved and the levels of emergency responses (level 1, level 2 and level 3) which depends upon the flood extent (district, state, cross-states, national).

3.2. The Potential Use of UAS in Flood Emergency Response

From the existing scientific literature, sixteen UAS applications that could be used in flood risk management activities were identified. The UAS applications can be assessed in terms of their use before an event in flood risk assessments, determining terrain elevations, flood extent modelling, identifying evacuation routes and flood warning. During an event to inform responders about actual flood extents, flood sources and routes, whether evacuation routes remain clear, identifying people in need of rescue and provision of emergency relief supply. Post events as part of damage and impact assessments. UAS raw products included high definition (HD) video, infrared imaging, Red-Green-Blue (RGB) imagery, RGB video, RGB video streaming and thermal imaging. A total of fourteen post-processing outcomes were identified: those derived from models (e.g., flood models, evacuation models), bespoke algorithms (e.g., image feature recognition), UAS-specific software (e.g., terrain elevation measurements) (Table 2).

Table 2. Detailed list of flood risk management components, with identified applications, UAS raw products and post-processed outcomes from the literature within the context of flood emergency response. The processing time for outcome generation and the accuracy of the outcome is also indicated. DEM, DTM and DSM stand for Digital Elevation Model, Digital Terrain Model and Digital Surface Model, respectively.

Flood Management Component	Applications	Examples	UAS Raw Product	Processed Outcome	Time	Details [3]
Flood warning	Evacuation warning	UAS with an embedded audible alarm to provide an alert about an upcoming flood and the need for evacuation (Mozambique).	N/A	N/A	Real-time	Flight path reach
Flood monitoring and flood risk assessment	Visualization of flood extent	Delineation of inundated areas by digitizing the boundaries at the contrasting land surface/water boundary [28].	RGB imagery RGB video	Flood extent, Ponding locations	Real time (<1 h)	0.2 m high resolution RGB imagery [4]
	Flood extent detection	Application of an algorithm to detect flood areas automatically [44,45].	RGB imagery	Orthoimage, flood extent	>48h [1]	0.2 m high resolution RGB imagery [4]
		A spectral difference index is generated from the RGB photos to map flood water extent [46].	RGB imagery	Orthoimage, flood extent	Real time (<1 h)	0.2 m high resolution in RGB imagery
	Modelling flood extent	A concept of transfer learning where a Convolutional Neural Network model is trained based on one dataset, transferred and used to classify another dataset to delineate flood extent [47]. A high accuracy terrain model combined with hydraulic calculations performed on transverse profiles produce the flood-prone areas at 1% and 5% exceedance probabilities of discharge [48]. A DEM mapped with UAS is used in hydrologic and hydraulic modelling to provide a flood hazard map [49].	RGB imagery	Orthoimage, DEM, flood extent	<48 h	1.5 cm ultra-high resolution in RGB imagery with 93% accuracy in flood extent
	Point measurement of flow velocity	A set of floating wireless sensors are deployed within the flood extent by multiple UAS to capture water velocity readings at multiple locations [50]. A combination of floating, infrared light-emitting particles and a programmable embedded colour vision sensor to simultaneously detect and track objects [51].	Water velocity readings. Infrared imaging	Water velocity	Real time (<1 h)	Estimated 0.15 m/s accuracy [5]
	Optical water velocity	Bespoke algorithms are used to track the movement of tracers [52], or texture [53–55] in the water surface in consecutive frames obtained from video footage.	RGB imagery RGB video streaming HD video	Orthoimage, water velocity Water velocity	>48 h [1] Real time (<1 h)	Estimated 0.5 m/s accuracy [5]
	Visual flood depth	Flood depth is estimated through the observation of wrack marks (post-event) [28] or via the observation of the water level (during event) against know height points (e.g., cars, bridges, feature buildings).	(Oblique) RGB imagery RGB video	Flood depth	Real time (<1 h)	High resolution RGB imagery
	Point measured of flood depth	UAS with ultrasonic sensors used to detect water level [56]. A pre-event DEM is required to estimate flood depth.	Water depth readings	Water level, point cloud, DEM, DTM, DSM	<48 h [2]	6 cm accuracy

Table 2. *Cont.*

Flood Management Component	Applications	Examples	UAS Raw Product	Processed Outcome	Time	Details [3]
	Flood source identification (fluvial, pluvial, groundwater)	Sources of flooding can be identified based on damaged caused within/outside the fluvial flood extent [15,57] or based on differences in water temperature [58].	RGB frames Thermal frames	Orthoimage, DEM, DTM, DSM	>48 h	1 m resolution (DEM)
Evacuation routes identification	Modelled evacuation route identification	Modelling of evacuation routes by using UAS as end devices of M2M architecture [59]. The input model needs DEM, DTM and/or DSM as well as hydrological/hydraulic input data.	RGB imagery RGB video	Map of evacuation routes, DSM, DTM, DEM, orthoimage	<24 h	20–60% tracking accuracy
	Surface changes and displacements of landslides	Surface changes and displacements of landslides [60,61].	RGB imagery RGB video	3D point clouds, DEM, orthoimage	<48 h [2]	1 cm ultra-high resolution (DEM), accuracy: 7.4 cm (horizontal) × 6.2 cm (vertical)
Damage assessment	Visual detection of affected properties, businesses, hospitals, schools	To collect information on damage to hospitals for patient rescue and for efficient allocation of resources [62].	RGB imagery	Location of affected properties	Real time (<1 h)	Resolution at building level
	Resistance and resilience measures identification	Identification of residential properties with resistance measures (i.e., flood aperture guards for doors and windows, flood resistant airbricks, and raised doors or steps leading to a property) [15].	RGB imagery	Orthoimage, DEM	>48 h	Resolution at building level
Rescue	Identification of safe shelter points	To identify where to best place NGO camps [21] and to identify land that could be safer to relocate families [20].	RGB imagery RGB video	Map with location of points	Real time (<1 h)	Resolution at building level
	Detection of stranded people	The use of UAS to locate stranded people [63,64] even at night [65,66] and specifically during floods [67].	RGB imagery RGB video Infrared imaging	N/A	Real time (<1 h)	Resolution at individual level
	Delivery of ad-hoc supplies	The use of UAS to deliver equipment or resources that guarantee the survival of stranded people e.g. to carry a radio to communicate [64], floating devices [65].	RGB imagery RGB video	N/A	Real time (<1 h)	Resolution at individual level

[1] A 36 h of photogrammetric processing is assumed [15] plus the time needed to apply the algorithm. [2] A 36 h of photogrammetric processing is assumed [15]. [3] When more than one study shows values of resolution and/or accuracy, it is indicated in the table the details of the lowest values for resolution and/or accuracy found. [4] Assumed the value of 0.2 m based on the real-time optical flood extent detection. [5] It is assumed that above 3 m/s, there are damages in the infrastructure [68], which is multiplied by the median of two coefficients of variation in flow velocity [52] to estimate the medium accuracy in m/s.

3.3. The UAS Deployment Analysis Matrix for England: Pre-, During- and Post-Event

Results (Figure 4) showed that pre-event for all catchment responses, the UAS applications were primarily concerned with digital elevation models for use in flood models, the condition of flood risk management assets, identification of safe shelter points and evacuation routes and providing warnings.

During the event applications providing information in real-time were prioritized. A combination of rapid visualization with high resolution of flood extent and flood depth were chosen. This can be provided with the current UAS technical capabilities. In fast response catchments, the participants' preference was for flow velocity with medium accuracy (instead of high accuracy). Additional time and costs are needed to achieve higher accuracies. Real-time applications relating to rescue activities (i.e., identification of safe shelter points, detection of stranded people and delivery of ad-hoc supplies) and damage assessment (i.e., visual detection of affected properties) were also identified as priorities. Participants stated that applications requiring more than 4 h of processing time to generate products are unlikely to be of use to responders in many flood events.

With the limitations of current UAS applications, the updating of evacuation routes was identified as being important only in catchments with a flood response longer than 12 h or where the duration of flooding in a faster responding catchment persists for more than 12 h. Applications that need more than 48 h of processing time, such as modelling flood extent and the identification of resilience and resistance measures, were still identified as being important as the data collected can be used subsequently to improve flood models and the response for future flood events.

During an event time is the priority, whereas after the event accuracy was most relevant. The focus in post event data collection was on the provision of more precise information for flood extent, flood depth and flood source so that flood impact can be estimated more accurately. After an event, there is also a continuing need for information that will assist with the rescue and recovery activities and the estimation of property level flood impacts.

3.4. Preferences in England for UAS Applications in Flood Emergency Response

The online survey evaluated the existing and desired processing time and accuracy in UAS applications for flood emergency response in England, as a way to determine whether technological development is needed to better inform emergency response. Results from the online survey indicated that 44% of participants currently have access to flood extent data within 12 h, with accuracies from 2 cm to 50 m. Only 3 of the 25 participants indicated they have access to flood extent data in less than 1 h with accuracies between 1 and 50 m. The preference of 52% of the participants was to have access to flood extent data within 0.5 h (i.e., near real time) with an accuracy of <10 m. There was also another significant group of participants (28%), who would seek to have access to flood extent data within 12 to 24 h with an accuracy of <10 m. Similarly, for flood depth and flow velocity respondents considered that having data more quickly with improved accuracy compared with the current products would be of benefit, with a desire for data to be available in <0.5 h with accuracies of 1 to 5 cm in flood depth and 0.1–0.5 m s^{-1} in flow velocity (Figure 5). There are current UAS technologies that are able to meet these requirements (Table 2).

Catchment flood response	Pre-event		During-event		Post-event	
Fast	- Evacuation warning [<1h, flight path reach]	7	- Evacuation warning [<1h, flight path reach]	7	- Flood extent [>48h, 0.2m resolution]	5
	- Flood source identification [>48h, 1m resolution]	4	- Flood extent [<1h, 0.2 m resolution]	9	- Flood depth [24-48h, 6 cm accuracy]	4
	- Evacuation route identification [12-24h, 20-60% tracking accuracy]	5	- Flow velocity [<1h, 0.15 m/s accuracy]	6	- Flood source identification [>48h, 1 m resolution]	7
	- Resistance and resilience measures identification [>48h, building level resolution]	7	- Flow velocity [<1h, 0.5 m/s accuracy]	8	- Surface changes and displacements of landslides [24-48h, 1 cm resolution]	7
	- Identification of safe shelter points [<1h, building level resolution]	5	- Flood depth [<1h, high resolution]	9	- Visual detection of affected properties [<1h, building level resolution]	7
			- Evacuation route identification [12-24h, 20-60% tracking accuracy]	5	- Detection of stranded people [<1h, individual level resolution]	4
			- Visual detection of affected properties [<1h, building level resolution]	7	- Delivery of ad-hoc supplies [<1h, building level resolution]	5
			- Identification of safe shelter points [<1h, building level resolution]	7		
			- Detection of stranded people [<1h, individual level resolution]	6		
			- Delivery of ad-hoc supplies [<1h, building level resolution]	8		
Medium	- Evacuation warning [<1h, flight path reach]	7	- Evacuation warning [<1h, flight path reach]	7	- Flood extent [>48h, 0.2m resolution]	4
	- Flood source identification [>48h, 1m resolution]	4	- Flood extent [<1h, 0.2 m resolution]	9	- Flood depth [24-48h, 6 cm accuracy]	4
	- Evacuation route identification [12-24h, 20-60% tracking accuracy]	5	- Flow velocity [<1h, 0.15 m/s accuracy]	8	- Flood source identification [>48h, 1 m resolution]	7
	- Resistance and resilience measures identification [>48h, building level resolution]	6	- Flow velocity [<1h, 0.5 m/s accuracy]	7	- Surface changes and displacements of landslides [24-48h, 1 cm resolution]	8
	- Identification of safe shelter points [<1h, building level resolution]	5	- Flood depth [<1h, high resolution]	9	- Visual detection of affected properties [<1h, building level resolution]	7
			- Flood source identification [>48h, 1 m resolution]	6	- Detection of stranded people [<1h, individual level resolution]	4
			- Evacuation route identification [12-24h, 20-60% tracking accuracy]	7	- Delivery of ad-hoc supplies [<1h, building level resolution]	6
			- Visual detection of affected properties [<1h, building level resolution]	8		
			- Identification of safe shelter points [<1h, building level resolution]	8		
			- Detection of stranded people [<1h, individual level resolution]	7		
			- Delivery of ad-hoc supplies [<1h, building level resolution]	8		
Slow	- Evacuation warning [<1h, flight path reach]	6	- Evacuation warning [<1h, flight path reach]	7	- Flood extent [>48h, 0.2m resolution]	4
	- Flood source identification [>48h, 1 m resolution]	4	- Flood extent [<1h, 0.2 m resolution]	8	- Flood depth [24-48h, 6 cm accuracy]	4
	- Evacuation route identification [12-24h, 20-60% tracking accuracy]	5	- Flow velocity [<1h, 0.15 m/s accuracy]	7	- Flood source identification [>48h, 1 m resolution]	7
	- Resistance and resilience measures identification [>48h, building level resolution]	7	- Flow velocity [<1h, 0.5 m/s accuracy]	6	- Surface changes and displacements of landslides [24-48h, 1 cm resolution]	8
	- Identification of safe shelter points [<1h, building level resolution]	5	- Flood depth [<1h, high resolution]	9	- Visual detection of affected properties [<1h, building level resolution]	7
			- Flood source identification [>48h, 1m resolution]	5	- Detection of stranded people [<1h, individual level resolution]	4
			- Evacuation route identification [12-24h, 20-60% tracking accuracy]	8	- Delivery of ad-hoc supplies [<1h, building level resolution]	6
			- Surface changes and displacements of landslides [24-48h, 1 cm resolution	4		
			- Visual detection of affected properties [<1h, building level resolution]	7		
			- Identification of safe shelter points [<1h, building level resolution]	7		
			- Detection of stranded people [<1h, individual level resolution]	7		
			- Delivery of ad-hoc supplies [<1h, building level resolution]	8		

Emergency response

Figure 4. Respondents' preferences in England for each UAS application in relation to catchment response and UAS deployment at different emergency response phases (before, during, post). The numbers indicate the number of participants. There were 10 participants, and therefore the maximum score possible is 10. Only UAS applications with a score ≥ 4 are shown as a means of indicating the majority opinion.

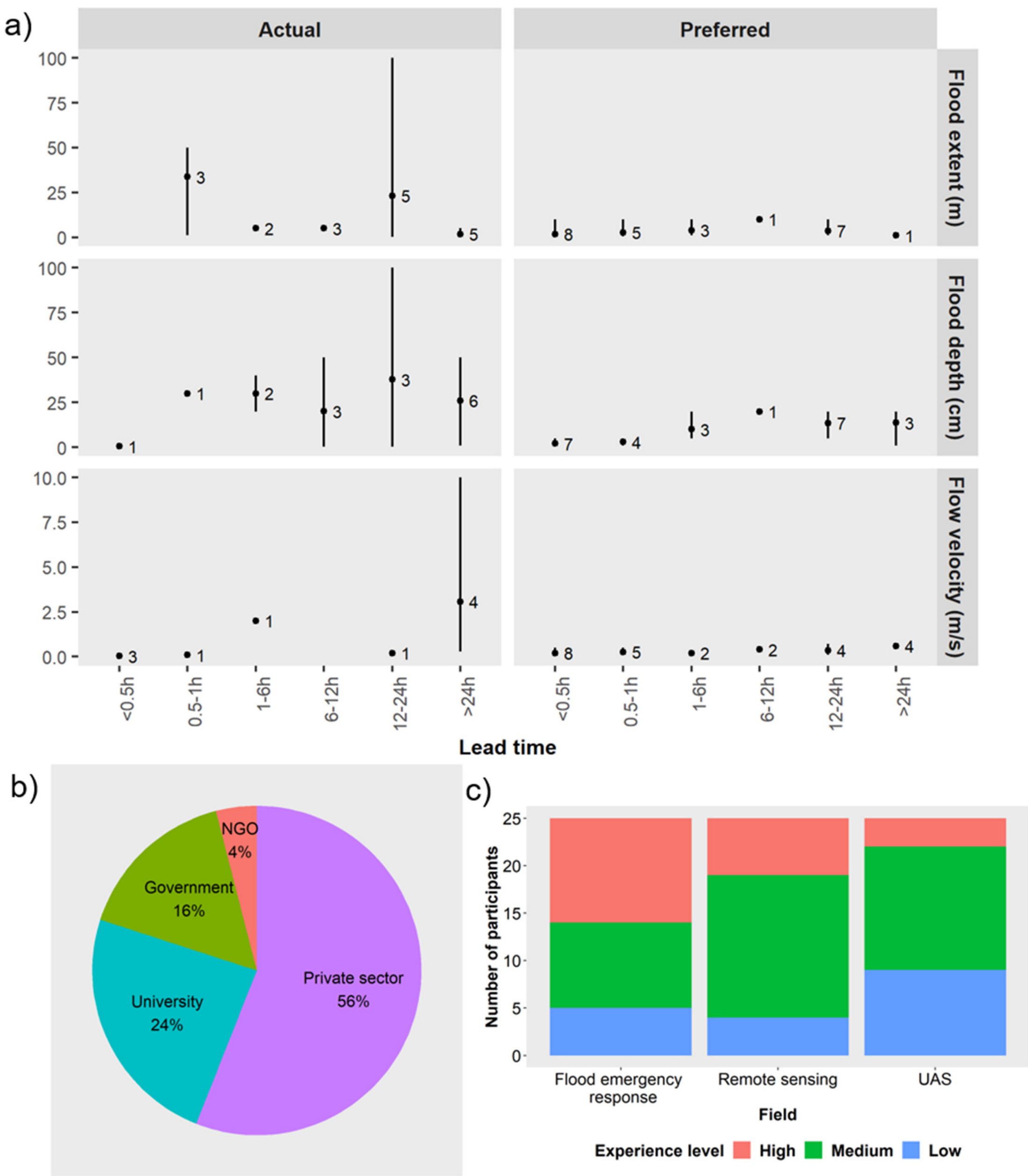

Figure 5. (**a**) Actual and preferred accuracy values and time needed to process flood extent, flood depth and flow velocity. The marker indicates the average of flood extent, flood depth and flow velocity, whereas the vertical lines shows the minimum and maximum values. The number of participants with a preference for a given combination are indicated against each measure. (**b**) Type of organizations that completed the survey. (**c**) Participants' experience level in flood emergency response, remote sensing and UAS. Results obtained from 25 participants.

For flood extent 13 participants considered time more important than accuracy when generating a product that will assist flood emergency response, whereas 12 participants thought accuracy was more important than time. Some participants stated that the most important factor for them was the trustworthiness of the data source. For flood depth (16) and flow velocity (17) participants were more interested in improved accuracy than in the time taken to obtain the data.

4. Discussion

4.1. A Purpose-Driven Approach to UAS Deployment in the Context of Flood Emergency Response

The operational use of UAS in flood emergency response is still limited [69]. A more systematic analysis of their application and capabilities in relation to their use in flood risk management including as part of an effective response to an event is, therefore, required if a purpose-driven approach to their deployment is to be realized.

During Storm Desmond in Cockermouth (Cumbria, England) in December 2015, more than 300 mm of rain fell over a 24 h period with an estimated <1% annual exceedance probability for both rainfall and river flows [70]. The Ministry for Housing, Communities and Local Government—Resilience and Emergencies Division (DCLG-RED), the Department for Environment, Food and Rural Affairs (Defra) and the Cabinet Office Briefing Room (COBR) were involved in coordinating the emergency response and supporting the local Cumbrian Strategic coordinating Group (SCG) [71]. UAS were used in Cockermouth during and after the storm to estimate the flood extent and identify impacted properties [72]. However, the use of UAS in Cockermouth could also have facilitated the identification of different types of flood sources (e.g., pluvial versus fluvial), as highlighted by [15]. In 2015 the range of applications UAS could be used for and how best to deploy them during flooding events had not been studied in a systematic way and, therefore, they were used in a reactive rather than strategically planned way.

Kerala is one of the Indian States that experiences the highest monsoon rainfall every year [73] and was affected by flooding in August 2018. The rain caused thousands of landslides in mountainous regions. Nearly 500 people died in the event [74]. Parts of the city of Cochin—the commercial capital of Kerala—were flooded, with a 90% increase in water cover and a water level rise of up to 5 m to 10 m [75]. As a result, major infrastructure assets including the airport, roads and railways had to be closed for safety reasons. The government issued evacuation orders and deployed the National Disaster Response Force teams within the area. During the emergency response over 223,000 people were evacuated to emergency relief camps [76]. UAS were used in Kerala to support rescue operations [77] and deliver aid [78]. There were also examples of people using UAS independently of the official response.

Although in both examples UAS were used in the response, the full capabilities were not necessarily exploited and the deployment of UAS was largely uncoordinated within the emergency response. The deployment analysis matrix developed here will enable those involved in flood risk management, including incident response, to take a structured approach to determining how best to use and deploy UAS within their specific context. The matrix-based approach will enable guidelines to be produced for the purpose-driven deployment of UAS within flood risk management activities including emergency response, as we discuss in the next section. This will help reduce duplication of effort and ensure the timely capture of important information that can be used to inform the current and future responses.

4.2. Guidelines for the Deployment of UAS within Flood Risk Management Activities Including Emergency Response

There are many benefits that can be derived from the use of UAS, to help reduce flood risk and the impacts on people, properties and the economy, if they are deployed in a structured and considered way that are currently not being fully utilized or exploited. The use of UAS has to be considered within the strategic planning for flood risk management activities including the response to flood events. This can build on experiences from the development of integrated flood forecasting, warning and response systems [79,80] and the use of real-time modelling to assist flood emergency response [81]. Our deployment matrix approach can be used as the basis for developing guidelines for the use of UAS within flood risk management before, during and post events. These guidelines are summarized in the following paragraphs.

Before a flood event:

- There is time to produce digital elevation and surface and terrain models which can then be used within flood models to estimate, for a given return period rainfall event, the likely extent, depth and velocity of flooding. The information produced can also be used to identify locations for temporary barriers, shelter points and evacuation routes.
- Flood models can be used to identify the likely fluvial, pluvial and coastal sources (e.g., [15]) and routes of flooding and can then enable potential evacuation routes to be identified (e.g., [82,83]).
- If flooding has been forecast for a particular area, UAS-based audio systems can be used to provide audible warnings to those at risk.

During a flood event:

- High levels of accuracy are often not a priority. The timeliness of the information being available to inform the response activities is paramount.
- Providing information in real-time is key as it enables effective prioritization of emergency response actions including: to identify where to deploy maintenance crews to deal with blockages and low spots in defences which are giving rise to unexpected sources of flooding; to identify whether the flooding is developing in line with modelled predictions in terms of extent and depth; to determine whether flooding is occurring in areas outside of those predicted by the models; to assess whether evacuation routes remain clear of flooding; to identify people and properties impacted by the flooding.
- During an event, typically time is limited to carry out new simulations [14]. During the event responders potentially identify gaps in the existing flood emergency plan (i.e., location of shelter points, evacuation routes, knowledge about resistance and resilience measures). However, in an event that exceeds the planned preparedness plan, it may be necessary to rerun the evacuation routes models.
- UAS can be used to determine the extent, depth and velocity of the flooding and the properties impacted. This information can be extremely valuable after the event to calibrate and refine the models and to determine whether additional flood risk reduction measures are required.
- Many organizations are involved in responding to flood events [81]. The use of UAS should be discussed well in advance of any need to deploy them including what information will be collected, how, by whom and for what purpose.
- UAS of the correct specification, including specified sensors and trained pilots will have to be available for deployment within an agreed standard of service.

After an event:

- UAS can be used to help determine the impact on people, properties and infrastructure, the flood extents and depths, and in identifying where best to deploy those still involved in rescue activities and in the recovery operations.
- UAS can be used to collect information that enable the calibration and validation of those models used pre-event for flood prediction purposes. Data collected at this stage will also look at features highlighting flood impact (e.g., properties affected). The EA with its strategic overview role for flood risk management in England would be well placed to develop guidelines for the use and deployment of UAS in this context and then to oversee their implementation.

4.3. Selecting the Correct UAS Platform

Multiple UAS platforms are available for use. The selection of the most appropriate platform for a particular application is a complex task. Factors that need to be considered include the capability of the gimbal to integrate the payload, weather conditions, the extent of the area to be flown, and the availability of pilots with the rights skills and regulatory permissions. UAS can be classified into vertical take-off-and-landing (VTOL), fixed wing and hybrids [84]. In Rivas et al. [85], the authors highlight that VTOL UAS are able to hover over a point and provide high resolution still imagery whereas fixed wing platforms enable wide area surveying [85,86].

The flooding of large areas, which will most likely occur in catchment areas with a slow response to floods, will require the use of fixed wing rather than VTOL platforms, as the former have longer endurance, although they are more difficult to fly and require specific training [87]. However, some fixed wing platforms do not have the capability of slowing down to speeds that enable them to collect high resolution imagery. Rivas Casado et al. [85] report 8 h to map the river channel of a 1.4 km reach, when using a rotor platform (Falcon 8 octocopter, ASCTEC, Krailling, Germany) whereas the same author reported a coverage of 142 ha within four hours in two flights undertaken with a Sirius Pro fixed wing [15]. Fixed wing platforms such as the Sirius Pro enable flights of up to 50 min at a cruising speed of 18 m s^{-1} [88]. In certain locations, VTOL UAS will also be required to overcome the limitations of terrain in terms of take-off and landing [19]. VTLOs can hover on site with high location accuracy and, therefore, take more detailed photographs at locations of interest. Hybrid models are able to combine the advantages of both fixed wing and VTOL platforms. The WingtraOne PPK VTO is a hybrid rotor and fixed wing platform able to provide Ground Sampling Distances of 0.7 cm/pixel and map 400 ha in a single flight [89]. The battery endurance is 55 min. The platform is able to fly under wind conditions of up to 45 km h^{-1} in cruise and up to 30 km h^{-1} for landing.

Battery endurance can also compromise performance. Overall, fixed wing platforms provide better battery endurance than VTOL platforms. Figure 6 and Table 3 show an alternative classification for UAS based on battery endurance and work range. Low-cost close range UAS include platforms with a range of generally up to 5 km and an endurance time of less than 45 min. Examples of such platforms include standard small VTOL platform such as the DJI Phantom 4 Pro (DJI Technology Co, Shenzhen, China) which can fly continuously for over 30 min [90] at a maximum speed of 20 m s^{-1}. Such platforms will be suitable to cover small catchments or specific areas of medium to large catchments. More expensive close-range platforms offer a working range of up to 50 km with battery endurance of up to 6 h. The mdMapper4-3000DμoG VHR VTLO (microdrones) is an example of such a platform able to capture RGB imagery at a ground sampling distance (GSD) of up to 0.6 cm/pixel [91]. The platform has an endurance of approximately 40 min when flying at an altitude of 120 m. The UAS can cover between 64 ha (80 mm lens, GSD = 0.6 cm/pixel) and 150 ha (35 mm lens, GSD = 1.3 cm/pixel) at a constant speed of 5 m s^{-1} within a single flight. A fixed wing example of a close-range platform is the Sirius Pro (Topcon Positioning System Inc., Livermore, CA, USA) which has a 50 min flight endurance and is able to operate under windy conditions (50 km h^{-1}) with gusts of up to 65 km h^{-1} [92]. Another example is the eBeeX which is able to gather RGB imagery at 1 cm/pixel and cover 220 ha in a single flight when flying at an altitude of 120 m. Short-range, medium-range and high-endurance platforms all require runways for their deployment and, although they provide a larger working range and endurance, are difficult to deploy in urban settings, especially during flood events.

In large flooded areas, there is likely to be a need to coordinate the deployment of multiple UAS within an affected area. The surveying of large areas will result in larger data sets and this will have a consequential impact on the time taken to generate products. More stable and perhaps heavier platforms, such as the microdrone md4-1000 [93], are needed for more extreme wind and rainfall conditions. Additional advances will enable the miniaturization of sensors, enhance the level of autonomy, increase battery life and the capability of flying in more extreme weather conditions.

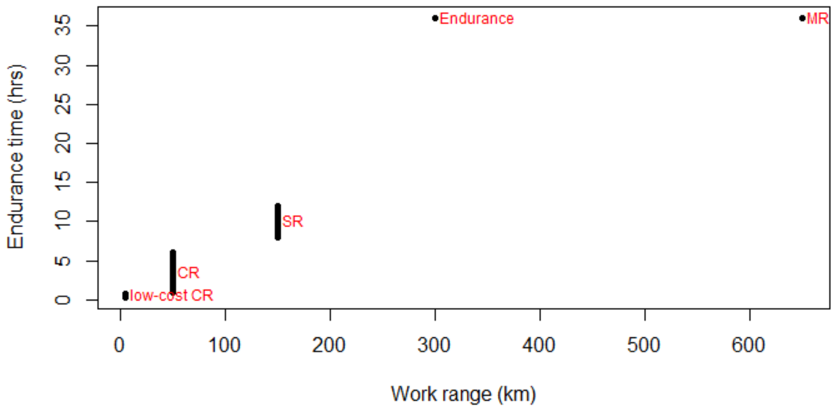

Figure 6. Simplified classification of UAS platforms based on their work range (km) and battery endurance time (h). The different classes include low-cost close-range (CR), close-range (CR), short-range (SR), medium-range (MR) and high-endurance (Endurance) platforms. A full description of these classes is provided in Table 3.

Table 3. Description of the simplified classification of UAS.

UAS Type	Range (km)	Endurance Time (h)	Remarks
Low cost close range	5	1/3—3/4	This type includes Micro and Nano air vehicles, low altitude flying with a maximum altitude of ca. 1000 m, no need for runways.
Close range	50	1—6	Need runways, altitude up to ca. 1500 m.
Short range	150	8—12	Need runways, altitude of a few thousand meters.
Mid-range	650	-	Need runways, altitude up to 9000 m.
Endurance	300	36	Need runways, altitude of 20,000 m or more.

4.4. The Deployment Decision Approach to an Indian Context

Our deployment analysis matrix approach for the use of UAS in flood risk management activities in England has the potential to be transferred to other countries (e.g., India) with different climatic, topographic and socioeconomic contexts. In India, environmental conditions can be extreme in terms of the intensity and extent of the rainfall. Transferability of the matrix will need to take into account the catchment response. In India, some catchments are of a larger scale than those in England and can be flooded for weeks with a need for recurrent monitoring of large areas. One of the challenges faced is the need to evacuate large numbers of people over extended areas in a short period [82]. The size of the areas affected will require the deployment of certain types of UAS (Section 4.3) for particular applications. In India, rural areas can also present access, travel time and maintenance challenges [82,94] with landslides limiting access to remote areas [95,96].

5. Conclusions

UAS are currently used in a largely ad hoc manner in flood risk management activities with practice differing significantly even within countries. Even so, their use has proved to be beneficial. However, if they were to be used in a purpose-driven and strategically coordinated way, they can provide more coherent and targeted information that will have added value for flood risk management activities, including during the response to events. The data and information produced by UAS can be used to improve flood risk management activities, structures, tools and approaches helping to reduce flooding and its associated impacts on people, properties, infrastructure and the economy.

We have identified a range of products that can be delivered by UAS and have developed an analysis matrix approach to help target their deployment. The UAS deployment matrix forms the basis for developing guidelines to assist those involved in flood risk management activities, including emergency responders, in developing a more strategic and targeted approach to the use of UAS before, during and after flood events. The approaches developed will need to be context specific including who will use what type of UAS and for what purpose before, during and after an event. The deployment matrix we have developed for England has the potential to be translated into an Indian context, and in other countries.

Further research should focus on exploring future technological developments of UAS platforms and sensors, their potential applications within a flood emergency response context and how these will feed into the existing deployment guidelines. Technological developments would be particularly helpful in the miniaturization of sensors, their integration on more stable UAS platforms and increased flight (i.e., battery) endurance. The fast pace of technological advances within the field of UAS requires a flexible and adaptive approach, which facilitates operational uptake as soon as advances are commercially available. The various organizations involved in the use of UAS in flood risk management will have to keep the deployment guidelines under review if they are to make the best use of the available and developing technologies to achieve flood management and resilience targets.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/2/521/s1, Table S1: Organisations involved in the flood emergency response in England and India and their associated role.

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